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AIRFIELD DAMAGE REPAIR (ADR); POLYMER REPAIR OF AIRFIELDS SUMMARY OF RESEARCH

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14. ABSTRACT
Several resin-based binders produced by Ashland Chemical were investigated for use with indigenous aggregates for rapid repair of damaged airfield pavements. The resin was required to be non-flammable and have at least 30 minutes of working time. Only a 1:1 blend of Pliodeck® TPO Membrane adhesive and Pliodeck® PVC Membrane adhesive were found to meet these requirements. The effects of aggregate type, temperature, and moisture on the polymer concrete behavior were evaluated. Small scale field tests were conducted to optimize mixing procedures, and cylindrical specimens were made to determine compressive strength, tensile strength, modulus of elasticity, and Poisson's ratio. Polymer concrete made with Pliodeck® was found to be an impractical material for rapid runway repair because it has a low modulus of elasticity and poor workability. The implementation of Pliodeck® polyurethane polymer concrete was not recommended because of the very short working times associated with the coarse aggregate mixtures as well as aggressive foaming and segregation problems.

15. SUBJECT TERMS
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Executive Summary

Relevance

Polymer concrete mixes composed of Ashland Speciality Chemicals Company Pliodeck® resin-based binders and indigenous aggregates were investigated for use as rapid repair materials for aircraft operating surfaces. Research factors included resin type, fine aggregate type, aggregate moisture content, mixing temperature, and curing temperature. The resin-based binder was required to be non-flammable and to have at least 30 minutes of working time. Only a 1:1 blend of Pliodeck® TPO Membrane adhesive and Pliodeck® PVC Membrane adhesive, were found to meet these requirements.

Recommendations

Polymer concrete made with Pliodeck® was found to be an impractical material for airfield damage repair because of low stiffness and poor workability. The implementation of Pliodeck® polyurethane polymer concrete is not recommended because of the very short working times associated with the coarse aggregate mixtures as well as aggressive foaming and segregation problems. The resin material was found to be not universally applicable across a range of environmental conditions.

Other possible uses of the polymer stabilized base should be evaluated. The aggregate-filled foam technology with Pliodeck® created a strong porous mass suitable for pavement base applications. Pliodeck® foam strengthened the coarse aggregate and allowed water to pass easily through, thereby limiting subgrade settlement. Erosion protection and soil stabilization are several other uses of polymer concrete that could be investigated.

Rationale

Workability of the polymer concrete was dependent on aggregate pH, temperature, moisture and mixing time. Mixing time affected the rate and time of foaming and the working time. During the foaming process, coarse aggregates segregated to the bottom of the container. Mixing the polymer concrete longer reduced segregation but resulted in rapid foaming and reduced working time. Shorter foaming time periods were due to an increase in the rate of polymerization with longer mixing times. When the polymer concrete was mixed through the foaming phase, all workability was lost because the material became too stiff. In addition to mixing speed, high pH, high temperature and high moisture reduced the polymer concrete working time.

1. Introduction

The Air Force Research Laboratory (AFRL) initiated research under Air Force Rapid Runway Repair (RRR) Program Task Order Contract Number F08637-03-C-6015 SEAMAS Supplemental Support Group (SSG) Subtask: Polymer Technology for Agile Combat Support to develop a rapid crater repair using resin binders for indigenous materials. The research team consisted of Ashland Specialty Chemicals Company (Ashland), Palmer Manufacturing and Supply, Inc. (Palmer), and the University of Texas at Austin (UT). Ashland, a producer of thermoset polymers with extensive experience with resins including foundary sand resins, produced the polymer binder. Ashland along with Palmer, a manufacturer of continuous aggregate mixers for the foundry industry and polymer concrete applications, developed large-scale mixing equipment. UT's role was to determine material properties and perform stress analyses of the repairs. Both Ashland and Palmer advised UT on batching procedures and material behavior.

This research was executed in two phases over a period of two years. Phase I was primarily concerned with evaluating several polymers for suitability in rapid airfield repair according to USAF requirements. The UT team evaluated several candidate Ashland polymer compounds including aromatic polyurethane, aliphatic polyurethane, a furan resin, a sodium silicate polymer, a polyester resin, and moisture-cured polyurethane. All but one of these binders were found unsuitable after the thermal analysis and flammability testing. Only the moisture-cured polyurethane warranted further evaluation, but its density, set time and strength were issues. In this phase, an analytical approach was also developed to determine the stresses in the repairs using a wide range of assumed base and loading conditions. The results of the research allowed determination repair thickness for a range of expected conditions.

The objective of Phase II of this research was to explore the potential of a 50/50 blend of Pliodeck® thermoplastic poly olefine (TPO) membrane adhesive and Pliodeck® poly vinyl chloride (PVC) membrane adhesive for suitability as a binder for polymer concrete and polymer stabilized base. The polymer concrete and stabilized base was proposed to be used by the military with indigenous aggregates for rapid construction in airfield damage repair (ADR) applications, in particular, for crater repair. Phase II also focused on identifying a range of representative aggregates and their properties related to polymer concrete.

2. Problem Definition

The primary focus of this research was the study of polymer concrete as a crater repair material. Two crater repair systems were studied. The first repair system assumed a runway crater filled with a polymer concrete structural cap over debris, whereas the second repair system had a three-layer repair of polymer stabilized base over debris with a polymer concrete cap. These systems are shown in Figure 1 and Figure 2, respectively. Repair layer thicknesses depend on material stiffness and loading conditions.

The USAF defines rapid repair as requiring a maximum of four hours from the time repair mobilization is initiated to repair completion and opening the runway for aircraft take-off and landing [1]. At least 15 to 30 minutes of working time with the polymer concrete at room temperature (72^{o}F) is also required. Workability is defined by the Portland Cement Association as "the ease with which [freshly mixed Portland cement concrete] can be mixed, placed, molded, and finished [2]".

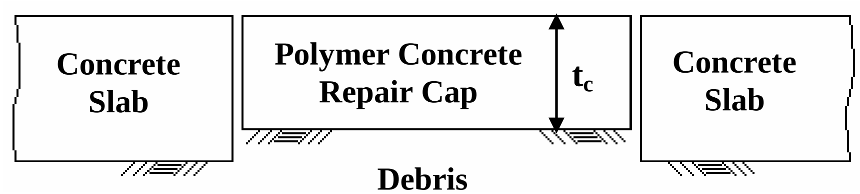

Figure 1. Two-layer Repair System

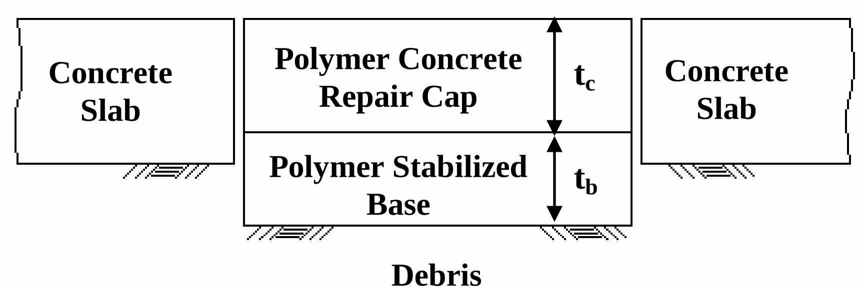

Figure 2. Three-layer Repair System

Properties related to workability are "consistency, segregation, mobility, pumpability, bleeding and finishability" [3]. For this research, workability was defined similarly. Important workability properties for the polymer concrete were stickiness, malleability, mobility and finishability. Because this research was for the rapid repair of bomb-damaged runways, the USAF also stipulated 2- and 24-hour flexural strengths of 1,200 and 1,500 psi, respectively, for the polymer concrete cap material. Over the past 30 years this strength requirement has increased from 400 psi because of increase in weight of aircraft using these runways. The required compressive strength of the polymer concrete cap material is 3,000 psi. These requirements were used to develop guidelines for a quality control program that could easily be applied to polymer concrete repair.

Quality control, or process control, is defined by the Federal Highway Administration (FHWA) as those quality assurance actions and considerations necessary to assess and adjust production and construction processes so as to control the level of quality being produced in the end product. Quality assurance addresses the overall problem of obtaining a quality of service, product, or facility in the most efficient, economical and satisfactory manner possible. Such a method includes all those planned and systematic actions necessary to provide confidence that a product or facility will perform satisfactorily in service [4]. Quality control can be simplified into a few general principles that are easily applied to various materials. First, specifications for raw materials are established. These raw materials are tested, and the results are then used to modify the specification of processing. Tests occur at intermediate stages of production from which the results are used to either modify the product or if necessary, reject the product to avoid further financial loss. Lastly, testing of the final product occurs to ensure construction was completed within specifications [4].

3. Phase I Research

3.1 General Overview

Various resin systems provided by Ashland were investigated in Phase I. These systems included aromatic polyurethane, aliphatic polyurethane, a furan resin, a sodium silicate polymer, a polyester resin and moisture-cured polyurethane. Table 1 lists the polymers used in this portion of the study. All of the resins showed promising results as a binder for a polymer concrete cap; however, all except the moisture-cured polyurethane were rejected because they were flammable [3]. Moisture-cured polyurethane has its advantages and disadvantages. A disadvantage to using water as a catalyst is that moisture in the air can trigger polymerization. Therefore, the resin must be stored with a nitrogen layer to prevent moisture from entering a previously-opened container. The advantages are that a second chemical does not have to be stored, and the resin may accommodate moisture in the aggregate better than other resin systems [3].

Table 1. Polymers Used in Phase I Research

Manufacturer	Brand Name	Generic Name
Ashland	PEP SET® XI 1000	Aromatic Polyurethane (PUB1)
Ashland	PEP SET® XII 2000	Aromatic Polyurethane (PUB2)
Ashland	PEP SET® 3501	Phenolic Urethane Catalyst (PUC1)
Ashland	PEP SET® 3325	Phenolic Urethane Catalyst (PUC2)
Ashland	PEP SET® 5140*	Aliphatic Polyurethane (AUB1)
Ashland	PEP SET® 5230	Aliphatic Polyurethane (AUB2)
Ashland	ACCOSET® 420SS	Sodium Silicate (SSB)
Ashland	ACCOSET® CII	Sodium Silicate Catalyst (SSC)
Ashland	CHEM-REZ® 284	Furan No-Bake Binder (FB)
Ashland	CHEM-REZ® C2009	Furan Catalyst (FC1)
Ashland	CHEM-REZ® C2019	Furan Catalyst (FC2)
Ashland	LB1101-06 AS	Unsaturated Polyester Resin
Ashland	Cobalt Octoate 12%	Promoter
Ashland	DMA	Promoter
Sigma-Aldrich	Luperox® DDM-9	2-Butanone Peroxide
Ashland	Pliodeck®	

Sieve analysis (ASTM C136), methylene blue (AASHTO TP57-99), specific gravity (ASTM C 128) and packing density tests (ASTM C 1252, Test Method C) were performed on sand samples. Mortar samples underwent thermal analysis, flexural (modification of ASTM C78 and ASTM C 580) and compressive testing (ASTM C 39), as well as elastic modulus (ASTM C 469) and density tests (ASTM C 642). The different materials were compared for each of the tests. CHEM-REZ® and ACCOSET® mixes were deemed unsuitable after the thermal analysis testing and were not used in further testing. The PEP SET® and polyester materials were favored until it was determined by Fowler et al [3] that non-flammable materials had to be used. Pliodeck®, with its water catalyst, became the most promising product, but density, set time and strength were issues and had to be addressed in future tests.

Moreover, analyses of the repairs were conducted to determine the stresses in the repairs using a wide range of assumed base and loading conditions. The results of laboratory strength tests permitted the thickness of repair to be determined for the range of expected conditions. The pavement analysis indicated that the most critical location for the wheel loads of an aircraft is at the exterior edge. Required thicknesses were determined for a wide range of variables: repair thickness and modulus, subgrade stiffness and polymer-stabilized base thickness and stiffness.

3.2 Resin System

The moisture-cured resin selected by Fowler et al [3] from Phase I research was a 50/50 blend of Pliodeck® TPO Membrane Adhesive and Pliodeck® PVC Membrane Adhesive (Pliodeck®). Ashland produces both resins for the roofing industry and custom blended the resin for this research. They are two competing types of thermoplastic waterproofing membranes consisting of reinforcing fibers sandwiched between two sheets of polymer based flexible matrix. Pliodeck® has a specific gravity of 1.16 g/cm^3 and a viscosity of 53.2 poise at 25^oC. The application process as a roofing membrane adhesive is performed in a few steps. First, Pliodeck® cans are prepared and mounted on an application cart. Second, breather holes are punched in the can, and the pour cap is removed. Finally, the adhesive is applied in beads by lifting a delivery lever and pushing the application cart as shown in Figure 3. The adhesive reacts with moisture in the air and foams. Once foaming commences, the membrane is placed. Membrane lockdown occurs in 30 minutes, and full cure is within 11 to 24 hours depending on temperature and humidity [3]. Ashland made proprietary modifications to the Pliodeck® to enhance its mechanical properties and cure times for use as a polymer concrete binder. Typical mechanical properties of polyurethanes, listed in Table 2, give an idea of the mechanical properties of Pliodeck®.

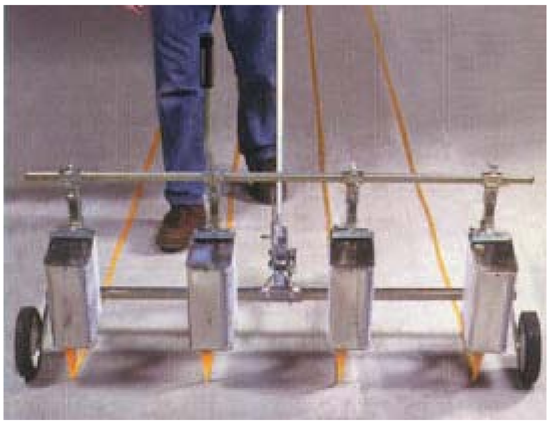

Figure 3. Application of Pliodeck® Membrane Adhesive [4]

Table 2. Estimated Polyurethane Mechanical Properties [4]

Property	Approximate Value
Density	74.8 pcf
Tensile Strength	4300-7000 psi
Modulus of Elasticity	3600-12000 psi
Tensile Modulus	1100-1250 psi

Pliodeck® is a polyurethane-based polymer made with aromatic isocyanates. One fundamental reaction for the formation of polyurethane foams, similar to Pliodeck®, is the reaction of isocyanates with water in one-component polyurethanes. The product is unstable carbamic acid, which splits into carbon dioxide and an amine. The amine then reacts with unused isocyanate while the carbon dioxide acts as a blowing agent creating the macromolecular skeleton. The water-isocyanate reaction is preferred for the manufacture of flexible foams. A balance of the blowing reaction and the polymer formation is necessary to have a rigid cell structure before collapse of the cell walls [3]. Aromatic isocyanates have higher reactivity over aliphatic isocyanates, and they turn yellow with time or when heated. Reactive one-component polyurethanes are relatively low molecular weight pre-polymers dissolved in small amounts of solvent and are cured by atmospheric humidity. When applied in a thin layer, the carbon dioxide does not form bubbles. When one-component polyurethanes are mixed with water, the reaction begins in the mixing chamber. A change in viscosity and temperature results from mixing; therefore, it is recommended that the material should spend a short residence time within the mixer. Low molecular weight one-component polyurethanes lead to brittle foams and loose bonds when used as a binder or adhesive. High molecular weight one-component polyurethanes have strong, flexible bonds when moisture cured. In short, a wide variety of polyurethanes can be built to meet a specific need, because there are several possible reactions with the isocyanate. One such reaction relative to Pliodeck® is the water-isocyanate reaction, because Pliodeck® is a moisture-cured one-component resin [3].

3.3 Analytical Behaviour of Polymer Concrete Repair

The objective of this part of the research was to investigate the analytical behaviour of polymer concrete (PC) repairs of portland cement concrete (PCC) pavements using the finite element program, EverFE [5]. The material properties of each layer, anticipated loading conditions, and desired quality of repair have to be determined or assumed before the stress analysis. Based on the stress analysis results, the criteria for thickness of polymer concrete repair considering significant variables were developed. Two repair scenarios were studied: (1) a two-layer repair consisting of polymer concrete cap and subgrade and (2) a three-layer repair consisting of polymer concrete cap, polymer stabilized base and subgrade [3].

Maximum stresses in the two-layer repair were first studied to identify the most sensitive variables for a polymer concrete repair. The sensitive variables were then studied for the three-layer repair. Thickness of repair, modulus of subgrade reaction (k-value), type of aircraft and loading locations were the more sensitive variables. The polymer concrete cap thickness ranged from 4 to 12 inches, using 2-inch increments. The k-values investigated were 50, 100, 300 and 500 psi/in, representing backfill with minimum compaction, compacted natural subgrade, granular base and cement stabilized base, respectively. Representative aircraft loading types were F-15, C-5 and C-17. Three loading locations were evaluated for the polymer concrete repair stress analysis: edge, interior and corner. Repair sizes were varied from 6 feet by 6 feet to 24 feet by 24 feet [4].

The EverFE rigid pavement analysis software [3, 4] was used for the calculation of the maximum stress values of the polymer concrete slabs in this study. EverFE is a public domain, three-dimensional finite element (FE) code developed at the University of Washington and now available from the University of Maine [5]. The EverFE program discretizes the region of interest (the pavement and subgrade) of a rigid pavement system into a number of elements with the loads at the top. EverFE couples a highly interactive graphical user interface for model development and result visualization.

This analytical exercise helped in understanding several variables in this research. First, the edge loading conditions for all design aircraft caused the highest maximum flexural stress values, with the F-15 edge loading condition being the most severe loading condition. Second, flexural stresses increased as the layer thicknesses increased. Third, minimal use of the polymer stabilized base reduced stresses in the polymer concrete cap. Also, the polymer stabilized base decreased the effect of the modulus of subgrade reaction on the cap stresses [3].

A sensitivity analysis was performed showing that Poisson's ratio had virtually no effect on the stresses in the two layer repair. The polymer concrete and polymer stabilized base moduli of elasticity; however, had a direct impact on the stresses and deflections of the repair. Low elastic moduli reduced the stresses in the cap and base, but increased cap deflections due to load. Therefore, the modulus of elasticity has a lower limit to avoid excessive deformation. Finally, smaller repair slabs performed better than larger slabs, but workability and maintenance must be accounted for in the selection of slab size [3].

A regression analysis was performed separately on the two-layer and three-layer repair scenarios with the F-15 edge loading case. The stress analysis results and the assumed material properties (shown in Figure 4) were used for the regression analysis. Two regression formulas (Equations 1 and 2) were developed from the regression analysis to calculate the required polymer concrete repair depth [3].

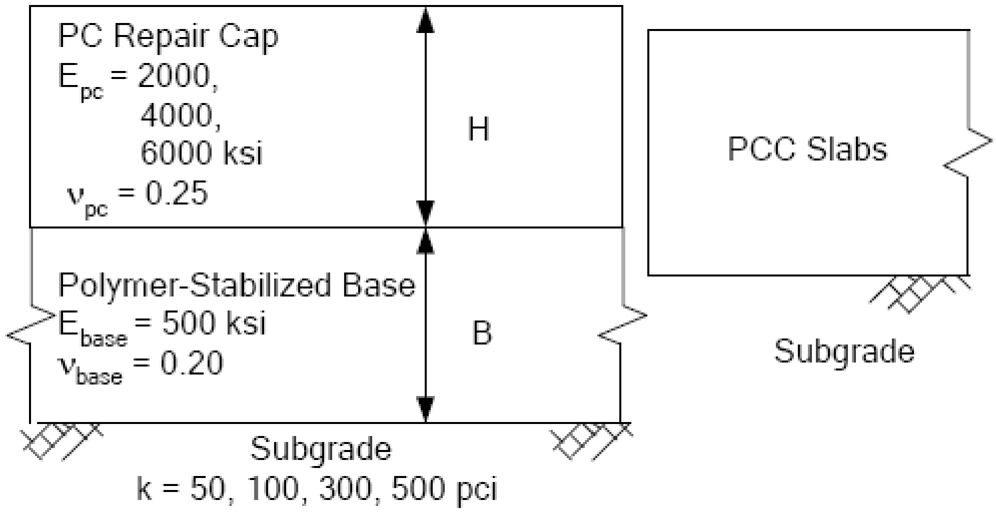

Figure 4. Assumed Input Variables for Regression Analysis [4]

Case I: Two-Layer Repair Scenario

$$\log(H) = 2.756 - 0.088\log(k) + 0.089\log(E) - 0.636\log(S) \qquad (3.1)$$

Case II: Three-Layer Repair Scenario

$$\log(H) = 2.497 - 0.097\log(k) + 0.408\log(E) - 0.365\log(B) - 0.889\log(S) \qquad (3.2)$$

where

H = required thickness of polymer concrete repair, inches,
k = modulus of subgrade reaction, pci,
E = modulus of elasticity of the polymer concrete cap, ksi,
B = thickness of polymer stabilized base, inches, and
S = allowable stress of the polymer concrete repair material, psi.

Material properties for the polymer concrete cap and polymer stabilized base were used as inputs for EverFE to determine maximum stresses in the polymer concrete cap. Only the worse case loading condition, the F-15 edge loading, and three-layer repair scenario were studied. It was observed that the modulus of elasticity has the greatest effect on the stresses in the polymer concrete cap. Moduli of elasticity for the polymer concretes were approximately 4 percent of the assumed lowest elastic modulus from the original analysis done without input from Pliodeck® TPO and Pliodeck® PVC. These extremely low moduli result in low stresses but extremely high deflections, hence material compatibility was the problem. The deflections in the polymer concrete repair were much greater than the deflections in the surrounding portland cement concrete pavement. According to the EverFE result, the polymer concrete cap material had too low a modulus for rigid airfield pavement repair.

A second analysis was performed with the regression formulas (Equations 1 & 2) to determine the thickness of the polymer concrete cap with and without polymer stabilized base. The inputs and thickness results are explained in detail in Fowler et al [4]. Allowable stresses of the polymer concrete repair materials were based on the 24-hour flexural strengths of the control polymer concretes. The results for the polymer concrete cap thicknesses with varying polymer stabilized base thicknesses were unrealistic because the regression formulas were developed for materials with higher stiffness. However, the results show that the cap thickness decreased when a polymer stabilized base was used.

In this phase, the EverFE solution and the regression formula solution were also used to determine the adequacy of the polymer concrete cap and polymer stabilized base as repair materials for a USAF runway pavement. Both solutions suggested that the two-layer and three-layer full-depth bomb damaged runway repair scenarios with Pliodeck® materials were insufficient to handle the F-15 edge loading case (worst case scenario). It was assumed in the analysis with EverFE that the pavement was rigid and the polymer concrete repair material had an elastic modulus greater than 500,000 psi. This analysis did not accommodate the extremely low moduli of elasticity of the polymer concrete. It was concluded that similar analysis with flexible pavement materials should be performed.

4. Phase II Experimental Tests and Quality Control

4.1 General Overview

In this phase, an experimental test program was designed to identify a range of representative aggregates and their properties related to polymer concrete [4]. These aggregates are used in batching and testing polymer concrete for a structural cap and polymer stabilized base. To determine the repair adequacy, several mechanical properties were evaluated at a range of temperatures, moisture contents and ages for the polymer concrete and polymer stabilized base. Mechanical properties evaluated include compressive strength, flexural strength, abrasion resistance, modulus of elasticity, Poisson’s ratio and coefficient of thermal expansion (COTE). The effects of coarse aggregates on the performance of the structural cap were investigated. Several aggregates were evaluated in a series of tests to determine appropriate controls for aggregate moisture, pH, grading and temperature. To determine the repair capability, flexural tests were performed on field specimens at a range of aggregate proportions, temperatures, relative amounts of resin and times of curing.

Based on the results of the experimental test program, processes and procedures were developed to evaluate indigenous materials at any given field site to determine their limitations for use as a repair material. Methods were investigated to rapidly calculate strengths of polymer concrete made from on-site materials. Aggregate stockpile properties were studied to establish the effective limits for the use of various indigenous materials in the runway repair. The field flexural test was included in the repair strategy to assess the potential of creating an adequate polymer concrete cap repair to support the required aircraft design loads.

4.2 Experimental Test Program

The experimental test program was divided into three parts: identifying a range of representative aggregates, determining mechanical properties of the polymer concrete used for the cap and determining mechanical properties of the polymer concrete used for the stabilized base. Standard ASTM test procedures were used as a guide in an attempt to capture basic material properties.

4.2.1 Aggregates

Several aggregates which are representative of a wide range of potential indigenous materials were selected based on grading, size and mineralogy. These aggregates were classified according to grading, packing density, absorption, shape and texture and mineralogy as described by Fowler et al [3]. Packing density and absorption are key variables used in material proportion calculations for concrete.

The fine and coarse aggregates selected for consideration are shown in Figure 5 and Figure 6 respectively. The fine aggregates in Figure 5 from left to right are Texas blasting sand, Tyndall sand, Colorado River sand and crushed concrete passing No. 4 sieve. In Figure 6, the coarse aggregates from left to right are crushed concrete retained on No. 4 sieve, river gravel and crushed limestone. These fine and coarse aggregates vary in color, size, shape and texture.

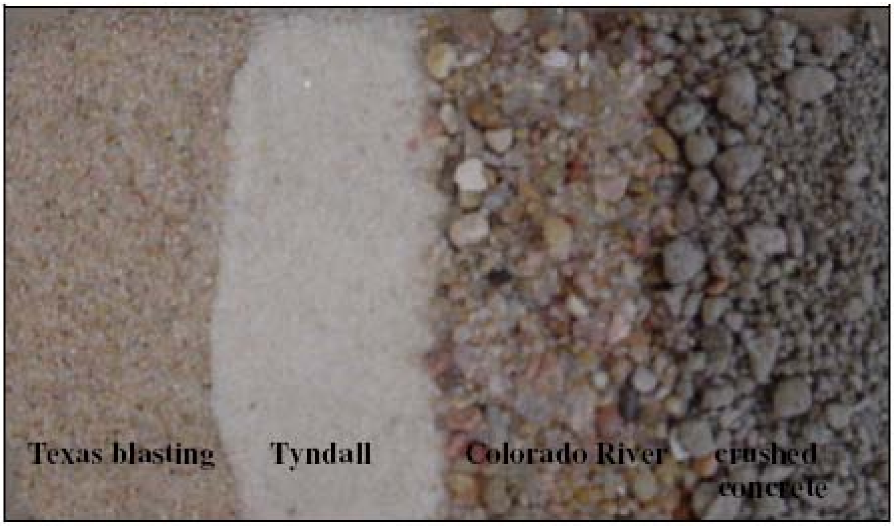

Figure 5. Fine Aggregates Selected for Study

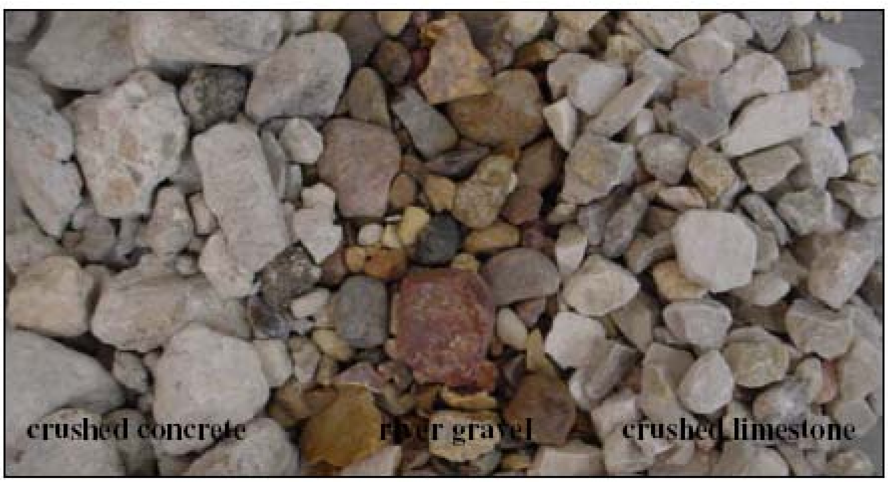

Figure 6. Coarse Aggregates Selected for Study

A sieve analysis (ASTM C 136), texture examination (visual for coarse and microscopic for fine) was done for both types of aggregates. The crushed concrete and Colorado River sand were well-graded fine aggregates as they had shallow, smooth grading curves. Well-graded aggregates are defined by a range of particle sizes. The Tyndall sand and Texas blasting sand were uniformly graded fine aggregates (marked by the steep grading curves) because these sands possessed particles of almost the same diameter. The three coarse aggregate had their grading curves fall closely together on the graph. The crushed concrete had greater quantities of larger aggregate compared to the crushed limestone and river gravel. The shape and texture of the four fine aggregates were analyzed visually with the aid of a microscope. The very fine Tyndall sand (homogeneous silica beach sand) had to be magnified five times to show its rounded and sub-rounded particles. Texas blasting sand was more angular and rough than the Tyndall sand when felt by hand. It was confirmed under the microscope as well. Texas blasting sand is typically used in sand blasting applications where the angularity of the sand is used as an abrasive. Colorado River sand magnified two times showed that it was a heterogeneous aggregate with rounded to sub-rounded particles. The crushed concrete had angular concrete mortar particles and built up mortar on the aggregate.

Other properties investigated include specific gravity and absorption (ASTM C 128), packing density (ASTM C 1252, Test Method C), and alkalinity. These properties are summarized in Table 3. Packing density is reported as the percent of uncompacted voids and alkalinity is reported as pH. The Colorado River sand has the lowest percent of uncompacted voids, because the aggregate particles are more rounded than the Tyndall sand, Texas blasting sand and crushed concrete. All of the aggregates have absorptions in the range of one to two percent except for the coarse and fine crushed concrete. The higher absorption of the coarse and fine crushed concrete is due to the cement particles acting like sponges. The most relevant aggregate property to this polymer concrete research is alkalinity. It was determined during batching of the polymer concrete cap material that aggregate alkalinity affected the material workability. Highly alkaline aggregate reduced the working time of the polymer concrete. All of the aggregates are in the base pH range (>7) with the Tyndall sand being the most neutral as it is the least alkaline. Crushed concrete and crushed limestone have the highest pHs because of their high calcium content.

Table 3. Summary of Aggregate Properties

Property	Specific Gravity	Uncompacted Voids, %	Absorption, %	pH
Tyndall sand	2.52	45.2	1.6	8.3
Colorado river sand	2.44	30.9	1.5	9.3
Texas blasting sand	2.61	46.2	1.1	8.6
Crushed concrete < No. 4	2.05	45.9	6.0	10.7
Crushed limestone	2.53	---	1.2	9.5
Crushed Concrete > No. 4	2.20	---	5.5	11
River gravel	2.51	---	1.7	8.3

4.2.2 Polymer Concrete Cap

Polymer concrete specimens were tested to evaluate compressive strength (ASTM C 39), flexural strength (modification of ASTM C 78 and ASTM C 580), modulus of elasticity and Poisson’s ratio (ASTM C 469), coefficient of thermal expansion (ASTM C 531) and abrasion resistance for the cap (ASTM C 944). Test variables used for compressive and flexural strengths were temperature, moisture and fine aggregate. Temperature and moisture were variables found to affect the mechanical properties of polymer concrete while the addition of clay did not [4]. In addition to temperature and moisture variables, specimens were also tested in flexure at ages of 2, 4, 8, 16 and 24 hours (measured from the time of mixing). A range of mechanical properties for the polymer concrete cap were determined with the four selected fine aggregates.

Ashland specified mixture proportions by weight of 30 percent resin, 1 percent water and 69 percent aggregate for the polymer concrete cap. The proportions were used consistently for the four fine aggregates. Materials were stored and mixed at room temperature that ranged from 72^{o}F to 78^{o}F, except when testing variable temperature. Control conditions were defined as room temperature material, mixing at room temperature, and 1 percent moisture. Oven-dry fine aggregate was mixed with water in a Kitchen Aid mixer at the lowest speed for one minute to evenly moisten the aggregate. Resin was then added to the moist aggregate and mixed for five minutes as suggested by Ashland [6]. However, the resin mixing time varied depending on the workability dictated by the fine aggregate. The actual mixing times are reported in section 4.3.1. Prior to mixing, the stainless steel bowl, paddle and molds were sprayed with an industrial silicone release agent, Zip-Slip. After mixing, the material was hand packed into the molds and screeded or cut to create a smooth, even surface.

Workability of the polymer concrete was dependent on aggregate pH, temperature, moisture and mixing time. For all mixtures, water and aggregate were mixed for one minute to evenly moisten the aggregate. Mixing time affected the rate and time of foaming and the working time. During the foaming process, coarse aggregates segregated to the bottom of the container. Mixing the polymer concrete longer reduced segregation but resulted in rapid foaming and reduced working time. The shorter foaming time periods were due to the fact that the rate of polymerization increases as the polymer concrete was mixed longer. When the polymer concrete was mixed through the foaming phase, all workability was lost because the material was too stiff. In addition to mixing speed, high pH, high temperature and high moisture reduced the polymer concrete working time. Crushed concrete and Colorado River sand were the most alkaline fine aggregates and Tyndall and Texas blasting sands were the least alkaline fine aggregates. Polymer concrete made with crushed concrete had half the working time of the Tyndall sand polymer concrete. The working time of the crushed concrete and Colorado River sand was reduced further, to a minute or less, at 100^{o}F and 1.5 percent moisture. On the other end of the spectrum, cooler temperatures and less moisture increased the working times of all of the aggregates. The polymerization reaction for Pliodeck® is exothermic. When the polymer concrete reaches its peak temperature, polymerization is nearly complete and therefore the polymer concrete is cured. Figure 7 is a plot of the times to peak temperatures for various fine aggregates.

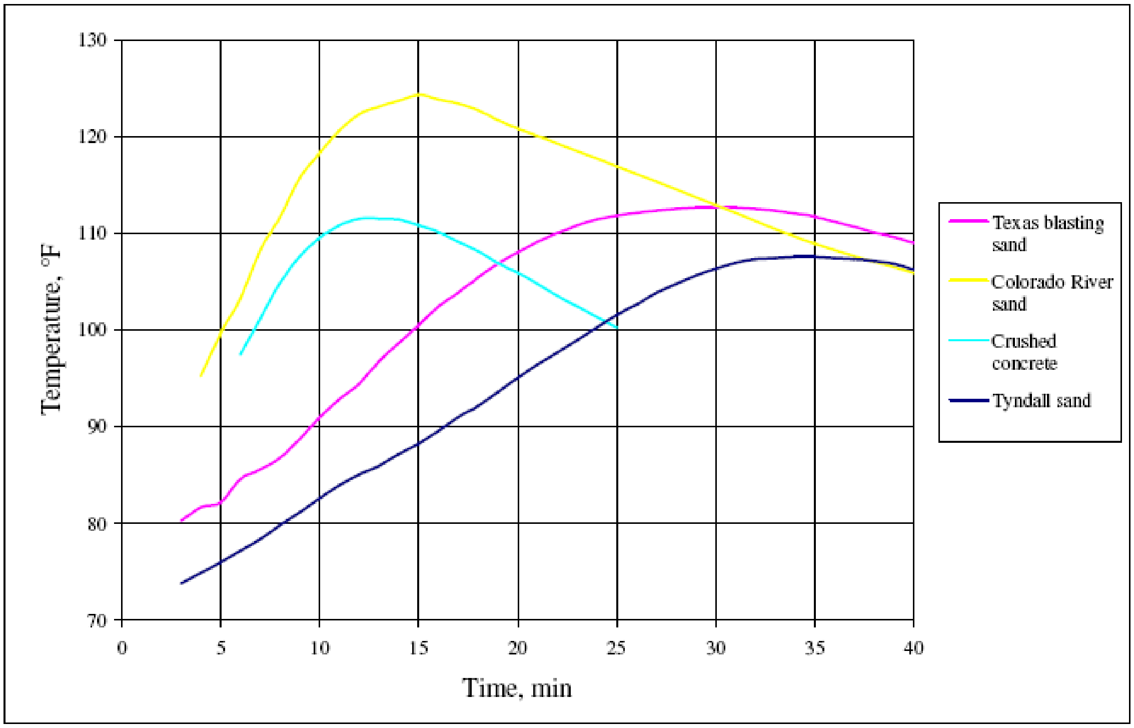

Figure 7. Polymer Concrete Thermal Analysis under Control Conditions

Low alkalinity aggregates gradually reached their peak temperatures in 30 to 35 minutes from the time the resin was added to the moist aggregate (see Figure 7 above). High alkalinity aggregates rapidly reached their peak temperatures in 10 to 15 minutes, half the time of the low alkalinity aggregates. A similar thermal analysis was also performed for the variable moisture and temperature conditions. Moisture had a significant effect on the polymer concrete exothermic behavior. The polymer concretes with lower moisture contents behaved similarly in that they slowly reached lower peak temperatures. Temperature also had a significant effect on the exothermic behavior. Polymer concretes made with 100°F material had the maximum peak temperatures, but only increased in temperature 10 to 30°F. The moderate change in temperature was due to the short working time of the 100°F material. The polymer concretes made with 40°F material peaked later than the 100°F polymer concretes and had temperature changes ranging from 50 to 80°F. Hence, it was concluded that Pliodeck® was sensitive to environmental conditions of moisture and temperature. Variable moisture and temperature conditions impeded the workability of the polymer concrete. Aggregate alkalinity further inhibited its workability.

The polymer concrete cap material was very flexible when compared to Portland cement concrete. Modulus of rupture beams exhibited elasticity by returning to the undeflected shape after failure. Beams failed when flexural cracks propagated from the bottom to the top of the beam in the middle third region, ultimately fracturing the beam. Colorado River sand, crushed concrete and Texas blasting sand reached 70 percent or more of their 24-hour flexural strengths in the first two hours after mixing.

These polymer concretes met the 2-hour flexural strength requirement of 1,200 psi minimum. Colorado River sand and crushed concrete also reached the highest overall flexural strengths, when compared to Texas blasting sand and Tyndall sand, and met the 24-hour flexural strength requirement of 1,500 psi. However, Tyndall sand and Texas blasting sand fell short of the USAF 24-hour flexural strength requirement. Flexural strengths were also found to be affected by the material temperature and curing temperature. Specimens at 100^{o}F and 40^{o}F had shorter working times and rapid polymerization as compared to room temperature specimens leading to lower flexural strengths. The results of 24-hour flexural strength testing with variable temperature can be found in Fowler et al [3]. Generally, the 100^{o}F and 40^{o}F specimens reached lower flexural strengths compared to the room temperature specimens. The 40^{o}F specimens resulted in brittle failures as they did not show signs of cracking before breaking under the load. However, these brittle failures occurred under higher stresses than the 100^{o}F beams. The lower flexural strengths of the 100^{o}F beams are accounted for by the short working times and rapid polymerization of Pliodeck®. Changing the moisture content or temperature from the control conditions of 1 percent moisture and room temperature reduced the flexural strength of the polymer concrete. The reduced strengths resulting from these variables did not meet the USAF 24-hour flexural strength requirement. Under control conditions, the crushed concrete and Colorado River sand exceeded both the 2- and 24-hour flexural strength requirements.

The compressive strengths of the polymer concrete ranged from 3,000 to 4,500 psi. Crushed concrete and Colorado River sand compressive strengths were on the higher end of the scale. Failure of the compression cubes was hard to determine because of the low modulus of elasticity of the polymer concrete. Cubes would compress, and no ultimate load was reached. The overall average modulus of elasticity of the polymer concretes made with Pliodeck® was 66,900 psi and the overall average Poisson's ratio was 0.31. The modulus was extremely low when compared to other polymer concretes, Portland cement concrete and asphalt concrete. The typical COTE for the polymer concrete ranged from 6 to 15 millionths in/in/^{o}C. Abrasion tests revealed that in most cases polymer concretes had good wearing surfaces because of their high abrasion resistance. Clay did not have a significant affect on the mechanical properties of the polymer concrete. Permian Red Clay was added in amounts of 1, 3 and 5 percent by weight of the fine aggregate to polymer concrete made with Tyndall Sand. However, slight losses in workability and higher peak exotherms were noted with increasing amounts of clay added to the polymer concrete. It was noted that the time to cure was cut in half with the addition of clay.

4.2.3 Polymer Stabilized Base

The polymer stabilized base was meant to bind coarse aggregate at the particle interfaces to increase the base load capacity, thereby increasing support for the polymer concrete cap discussed above. Five initial proportions, within the recommended range, were studied using 4-inch by 8-inch crushed limestone filled cylinders. Pliodeck® and water were mixed for 1.5 to 2 minutes, and then poured over the aggregate filled cylinders. After 24 hours the cylinders were demolded, measured, cut and tested in compression. A mixture ratio was selected based on the performance of these initial percolations/foaming backfill mixtures. The criteria for selection were compressive strength, depth of percolation, ease of pouring resin/water mix and time of foaming.

Two 4-inch by 8-inch cylindrical specimens for each coarse aggregate (river gravel, crushed concrete and crushed limestone) were made to study percolation, foaming and compressive strength. Five days after creating the six specimens they were demolded, measured, saw cut and tested in compression. The point of failure of the polymer stabilized base cylinders was subjective, because the specimen carried additional load in spite of the polymer skin tearing or pieces of aggregate having crushed. For consistency the maximum load was always determined when the aggregate crushed. The compressive strengths of the river gravel and crushed concrete specimens were greater than the initial proportion specimens. Percolating resin mixed with water over coarse aggregate proved to be a successful method to stabilize the aggregate. The polymer foam filled the aggregate voids and bound the aggregate to increase its load bearing capacity. However, the cylinder molds confined percolation and provided direct percolation paths around the perimeter. These concerns led to the investigation of different mixing methods and small scale field tests.

Three small scale field trials were conducted to study the performance of different mixing and percolation methods. Measured quantities of resin and water were mixed by hand and poured over crushed concrete in Trial 1. For Trial 2 resin was poured over wet aggregate, and in Trial 3 resin was poured over wet aggregate and then sprayed with water. A 24-inch diameter and 20-inch-deep hole was lined with plastic and filled with coarse crushed concrete within 6-inches of the surface. The dimensions were selected to permit five cylindrical cores to be taken for compressive testing. In all three trials, 4000g of Pliodeck® resin were used to achieve at least 6 inches of stabilized base as recommended by a previous EverFE pavement analysis. Resin and water, 18 percent and 6 percent by weight, respectively, were mixed by hand for two minutes with a wooden stick in a plastic 5-gallon bucket for Trial 1. Mixing the resin and water prior to pouring and percolation as performed in Trial 1 was the method used in the laboratory for making cylindrical specimens. Concerns that the mixed resin and water would follow the path of least resistance along the edges of the cylinder were confirmed with this field trial. For the second trial, 18 percent by weight resin was poured over wet aggregate. Results were substantially better than Trial 1. The resin uniformly percolated and reacted with water on the crushed concrete and foamed throughout the voids. The purpose of Trial 3 was to determine if the addition of partial mixing to Trial 2 would reduce the time to cure. After wetting the aggregate and pouring the resin evenly over the surface as in Trial 2, water was sprayed from a garden hose with nozzle over the surface for approximately 30 seconds, 10 seconds from three different directions. The foamed polymer was evenly distributed in the interstitial spaces between the aggregate and completely coated the aggregate from all sides. Thus, pouring resin over wet aggregate followed by spraying the aggregate with water was the recommended method for stabilizing the backfill as demonstrated in Trial 3. Both Trials 2 and 3 were successful methods of mixing and percolating Pliodeck® to stabilize base material as the foamed polymer was evenly distributed.

Compressive strengths were determined for the polymer stabilized base with each coarse aggregate by loading cylinders to failure. Compressive strength varied little for the three coarse aggregates with slightly higher strength using crushed limestone. The average tensile strength was 100 psi for the polymer stabilized base. Indirect tensile strength tests yielded ideal failure with a vertical crack through the center of the cylinder face. The moderate strength is good considering the porous matrix of the foam-filled aggregate. The average modulus of elasticity of the polymer stabilized base was 50,000 psi. The reported Poisson's ratio for the polymer stabilized base was 0.6. Theoretically, the upper limit of Poisson's ratio for incompressible materials is 0.5. A volume change was not indicated in the reviewed literature so the reported value is suspicious.

4.3 Quality Control (QC)

An experimental test program was developed to establish guidelines for the QC test methods. Coarse aggregates were introduced into the polymer concrete mixtures to study the effects on the cap performance. In an attempt to standardize the tests and limit variability, standard ASTM test procedures were used as references. Several test methods were investigated to incorporate a variety of potential influences on the polymer concrete cap behavior. These results were evaluated to create a strategy for developing specific QC tests. Finally, areas of concern were identified to ensure that stringent requirements could be implemented in order to control the quality of the finished polymer concrete repair. Several limitations were discovered during the investigation of various QC test methods. These limits helped to establish techniques for properly evaluating both indigenous materials and the adequacy of the actual pavement repair. A range of aggregate properties along with the flexural requirements of the polymer concrete was used to construct a satisfactory repair strategy for the polyurethane polymer concrete. After the actual quality control test requirements for both the aggregate properties and flexural strength were created, necessary equipment was identified to help facilitate the rapid runway repair.

4.3.1 4.3.1 Aggregates

Aggregate type greatly influenced the performance of the Pliodeck® resin polymer concrete. The pH of the material was the single most important property for the pavement repair. Simple tests were explored to quickly determine the pH of potential aggregates in field conditions. Both, hand-held pH meters and litmus paper tests were used to determine pH for fine aggregates. They were compared to laboratory values and it was concluded that both methods were good indicators of the actual aggregate pH range. Regardless of the advantages of being able to quickly obtain an accurate pH reading with the hand held meter, several disadvantages were associated with the instrument. To be employed in a wartime environment, the equipment should be extremely durable. However, this was not the case with handheld meters. The litmus paper was the desired method of quickly testing the pH of the aggregate in the field.

Aggregate temperature affected both the working time and the strength of the material during the experimental testing program. Hot aggregates shortened the available working time for casting the field beams with coarse aggregate, while lowering the flexural strength of the specimen as well. After analyzing the effects of temperature on different types of aggregate stockpiles, trends were developed to create ideal repair times when the material temperature would allow the longest working time. The peak material temperature occurred after the peak ambient temperature, while the stockpile gradually absorbed the heat from the surrounding environment. The fine aggregate stockpile displayed an overall higher temperature range than the coarse aggregate stockpile. The presence of voids within the coarse stockpile allowed the heat to escape more readily, while maintaining a temperature almost in equilibrium with the surrounding environment. Hence, it was observed that in hot weather, a runway repair with the Pliodeck® resin should be performed early in the morning hours, as the aggregate material would have the lowest temperature enabling greater workability with the polyurethane polymer concrete. If such an option were not possible, the aggregates should be stored out of direct sunlight to maintain a low material temperature and ensure ample working time for mixing and finishing the polymer concrete repair. Aggregates over 100^{o}F were not recommended for use with the Pliodeck® resin.

Because Pliodeck® is a moisture-cured polyurethane resin binder, moisture present in the aggregate influences the performance of the concrete material during mixing. The T-90 Trident Moisture Meter was used for tests of both fine and coarse aggregate stockpiles. The accuracy of this meter was evaluated with ASTM C 566. According to the manual, the readings obtained by the Trident meter were generally within two to three percent of the actual moisture level in the aggregate. The results from these tests support such a statement as the data collected from the ASTM C 566 indicate that the meter readings were within two percent of the actual values.

Although specific grading tests were not performed for this research, experience with the polyurethane resin material as well as literature reviews of past polymer research helped to established effective grading requirements. Coarse aggregates reduced the amount of resin needed for the polymer concrete repair. The maximum size of coarse aggregate was restricted to 1 ½-inch in order to maintain a finish acceptable for the USAF roughness criteria. A gap-graded aggregate mixture was preferred for the polymer concrete repair so a variety of aggregates could be incorporated into the repairs. The ability of the polyurethane resin to expand and fill the voids allowed the use of such a gap-graded mixture. By distinguishing between the separation of coarse and fine aggregates, relaxed grading requirements allowed the use of a wide range of aggregates types and sizes. Field test samples were collected for evaluating the grading of both the fine and coarse aggregates according to ASTM C 136. Aggregate grading did not have a significant influence on the performance of the polymer concrete repair. Therefore the coarse aggregate grading was limited to 90 percent material retained on the No. 4 sieve. The introduction of coarse aggregate into the mixtures lowered the amount of resin while at the same time decreasing the available working time.

The results of the relative density field test and the values of the actual specific gravity from previous tests were compared to conclude that the process was a reliable method to determine aggregate specific gravities for the calculation of material proportions by weight. The relative densities help to indicate the actual weight of aggregate necessary for the runway repair.

4.3.2 Field Flexural Test

Earlier work had indicated that flexural tests were extremely sensitive to loading method, temperature and loading rate. Hence, it was recommended that flexural strength alone should not be regarded as the deciding requirement for the adequacy of the polymer concrete repair. Sound engineering judgment in combination with the material properties should be incorporated into the evaluation of the structural repair.

4.3.3 Equipment

This research project investigated several products (instrumentation) based on both functionality and cost for effective field application. Products were recommended for testing aggregate moisture, pH, grading and relative density as well as field specimen flexural strength. Table 4 lists the various products along with their main function.

Table 4. Recommended Listing of Equipment for Field Testing

Product	Company	Purpose	Approximate Cost ($)
T-90 Trident Moisture Meter	James Instruments, Inc.	Aggregate Moisture	1423.95
ColorpHast pH 0-14 litmus paper	VWR	Aggregate pH	19.00
V12CF #150 12” diameter Brass 1-1/2” sieve	Gilson Company, Inc.	Aggregate Grading	66.00
V12CF #004 12” diameter brass No. 4 sieve	Gilson Company, Inc.	Aggregate Grading	66.00
CP-75 Compact Field Scale	Gilson Company, Inc.	Aggregate Grading, Relative Density	259.50
Dynalon 5000 mL Beaker	US Plastic Corp.	Aggregate Relative Density	26.30
HM-331 6 × 6 × 21 inch Plastic Beam Mold	Gilson Company, Inc.	Field Flexural Specimen	63.00
HM-1712 Portable Beam Tester	Gilson Company, Inc.	Field Flexural Strength	2050.00

5. Conclusions and Recommendations

This research identified characteristics of polymer concrete to be used as a structural pavement cap for USAF ADR applications. Properties of aggregate-filled foam technology, used as a stabilized base for USAF ADR applications, were ascertained. Pliodeck® was the binder for both the polymer concrete and the polymer stabilized base. A number of tests were performed to determine the feasibility of binding indigenous aggregates with Pliodeck® for rapid construction and repair of bomb damaged runways. A stress analysis was performed on a pavement repaired with the polymer concrete and polymer stabilized base to determine the suitability of the proposed ADR materials. This research also established aggregate quality controls for polyurethane polymer concrete. Procedures were developed to evaluate aggregates based on pH, temperature, moisture and grading. Coarse aggregates were introduced into the mixtures with the Pliodeck polyurethane resin to create flexural beams. During the study of the flexural performance of these beams, several constructability concerns arose. Finally, equipment was evaluated to limit cost as well as the amount of inspection gear required for use in the field. The entire research effort including phases I and II are summed up in the following section that provide brief conclusions and lay directions for future research.

5.1 Conclusions

The following conclusions were drawn from this study:

- Polymer mortar concrete 24-hour flexural strengths ranged from 1,400 to 1,800 psi, and the 2-hour flexural strengths ranged from 400 to 1,500 psi. Flexural strengths were greater for polymer concretes with alkaline aggregates. Compressive strengths ranged from 2,000 to 4,500 psi.
- Moisture and temperature affected workability and strength of the polymer concrete. Increasing or decreasing the moisture content in the polymer concrete resulted in lower flexural and compressive strengths. Similarly, increasing or decreasing the temperature resulted in lower flexural and compressive strengths. Ambient temperatures exceeding 80^{o}F and moisture contents greater than 1 percent reduced the working time of the polymer concrete.
- Pliodeck® was compatible with aggregates having different grading, shapes and absorptions, because these properties did not affect the behavior of the polymer concrete. Alkaline aggregates, however, reduced the polymer concrete working time, but resulted in rapid strength gain of the material.
- Aggregate-filled foam technology strengthened the coarse aggregate base. Compressive strength of the polymer stabilized base ranged from 500 to 700 psi and the average tensile strength was 100 psi.
- Performance of the polymer stabilized base was not affected by temperature or moisture. Aggregate grading and mixing procedure were the only deciding factors

for an adequate stabilized base. Wet, coarse aggregate larger than the No. 4 sieve was required for even foam distribution.

- The average modulus of elasticity and Poisson's ratio of the polymer mortar concrete were 80,000 psi and 0.3, respectively. The average modulus of elasticity of the polymer stabilized base was 50,000 psi. The reported Poisson's ratio for the polymer stabilized base was 0.6. Theoretically, the upper limit of Poisson's ratio for incompressible materials is 0.5. A volume change was not indicated in the reviewed literature so the reported value is suspicious. Both materials had extremely low elastic moduli; hence they were unsuitable as rigid runway pavement repair materials because they resulted in extremely high deflections when subjected to loadings by USAF aircraft.

- The 24-hour flexural strengths ranged from 500 to 900 psi for the 6 by 6 by 21-inch beams. The 2-hour flexural strengths ranged from 480 to 640 psi. The aggregate mixtures with a high pH displayed the greatest early strength gain for the polyurethane polymer concrete.

- Coarse aggregates reduced cost, because less resin was required for the mixtures. These mixtures had very short working times (less than five minutes) at various temperatures. The flexural field beams not only had rough finished surfaces but also very low flexural strengths compared with the mortar beam tests previously performed. The ideal ratio of coarse to fine aggregate was discovered to be 1:1.

- Beams cast with 25 percent weight of resin exhibited larger flexural strengths for the field beams ranging from 1,000 to 1,200 psi. Ashland's recommended 30 percent weight of resin was not the most efficient use of the polyurethane binder for coarse aggregate mixtures.

- Litmus paper tests adequately identified aggregate pH ranges to determine alkalinity. High pH aggregates greatly reduced the working time of the polymer concrete.

- Increasing aggregate temperature decreased the overall working time and reduced the flexural strength for the field specimens. Thus the recommended mixing time was determined to be the early morning hours just before sunrise when stockpiled aggregates were at the lowest temperature.

- The influence of aggregate moisture on polymer concrete performance decreases as the size of the repair increases. The required 1 percent weight of moisture was hard to regulate, thus excess moisture was desirable to ensure the entire amount of resin has been completely polymerized to bind all of the aggregate material.

- The use of a gap-graded mixture allowed a wide range of material in both size and texture to be considered, as a No. 4 sieve separated the fine and coarse aggregates.

- The polymer concrete made with Pliodeck® is an impractical material for rapid runway repair because it had a low modulus of elasticity and poor workability. The implementation of Pliodeck® polyurethane polymer concrete is not recommended because of the very short working times associated with the coarse aggregate mixtures as well as the aggressive foaming and segregation problems.

Too many influencing variables created a complex repair scenario as the resin material was not universally applicable across a range of environmental conditions.

5.2 Recommendations

The following recommendations were made based upon conclusions from this research:

- Workability of the polymer concrete was a concern because of Pliodeck's sensitivity to temperature, moisture and alkalinity. Further investigation of the resin should include tailoring Pliodeck® additives to eliminate the foaming reaction with water and to reduce the rate of polymerization at high temperatures. Another possibility to increase the working time with the polymer concrete would be a construction method to harness the foaming time and still build a dense repair. Developing the method would require several expensive large-scale field tests.
- Aggressive foaming and a short working time were some important constructability issues associated with the control of the Pliodeck polymer repair. Further work should concentrate on eliminating the foaming to prevent the segregation of coarse aggregates and the expansion of the material volume. Compatibility with high pH aggregates is necessary for creating a universal polymer repair material. Additional additives should be investigated to counteract the high alkaline aggregates. The regulation of only 1 percent weight of water during the mixing process is unrealistic in field conditions. Water-cured polyurethane resin development should continue toward discovering a material unaffected by excess moisture as well as extreme temperatures.
- The test method used for modulus of elasticity and Poisson's ratio was for stiff materials such as portland cement concrete. As the polymer concrete had a very low stiffness, the test method was modified to gather deformation readings. The accuracy of the modulus of elasticity and Poisson's ratio test performed was unknown. It was recommended that these two properties be evaluated with other test methods for visco-elastic materials and polymeric materials.
- Moreover, other possible uses of the polymer stabilized base should also be evaluated. The aggregate-filled foam technology with Pliodeck® created a strong porous mass suitable for pavement base applications. Pliodeck® foam strengthened the coarse aggregate and allowed water to pass easily through, thereby limiting subgrade settlement. Erosion protection and soil stabilization are several other uses of polymer concrete that can be investigated.
- It was recommended that other rapid repair materials should also be investigated. Ductal®, a new construction material technology, is characterized by very high durability, compressive strength and flexural resistance. However, cost would be one of the limiting factors of such customized high end material.

6. References

1. Air Force Pamphlet (AFPAM) 10-219, Volume 4, *Rapid Runway Repair Operations*
2. Portland Cement Association, *"Glossary"*, http://www.cement.org/bookstore/supporting/cd100/Glossary/Glossary.pdf, access 26 Dec 2008.
3. Fowler, David W., Pamela Pietrasik, and Chul Suh. *Final Report – Task 5.14.* The University of Texas at Austin, July 28, 2005.
4. Fowler, David W., Carrie Marr, Michael Osburn, and Chul Suh, *Final Report – Task 5.18.* The University of Texas at Austin, October 1, 2006.
5. University of Maine, "EverFE: Software for the 3D Finite Element Analysis of Jointed Plain Concrete Pavements," http://www.civil.umaine.edu/EverFE, accessed 25 Feb 2008.
6. Singh, Rina. *Final Report – Task – 4.0.2.* Ashland Specialy Chemical, July 28th 2006.